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A novel approach for selecting typical hot-year (THY) weather data

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HIGHLIGHTS

- The impacts of heat wave on outdoor and indoor environment are different.
- The heat wave impacts are not sensitive to the envelope performance in this study.
- A novel approach was developed to determine typical hot year weather data.
- The derived heat waves data are different from the outdoor-based results.

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ABSTRACT

The global climate change has resulted in not only warmer climate conditions but also more frequent extreme weather events, such as heat waves. However, the impact of heat waves on the indoor environment has been investigated in a limited manner. In this research, the indoor thermal environment is analyzed using a building performance simulation tool for a typical residential building in multiple cities in China, over a time period of 60 years using actual measured weather data, in order to gain a better understanding of the effect of heat wave events. The simulation results were used to analyze the indoor environment during hot summers. A new kind of weather data referred to as the typical hot year was defined and selected based on the simulated indoor environment during heat waves. The typical hot-year weather data can be used to simulate the indoor environment during extreme heat events and for the evaluation of effective technologies and strategies to mitigate against the impact of heat waves on the energy demand of buildings and human health. The limitations of the current study and future work are also discussed.

1. Introduction

With the increasing impact of its frequency and magnitude, climate change remains as one of the most serious environmental issues humanity has ever faced. According to the World Meteorological Organization (WMO), 2016 was the warmest year ever recorded and the period from 2013 to 2017 was the warmest five-year period on record [1]. The increasing effect of climate change is not only exemplified by an increase in the median temperature, but also by the occurrence of more frequent extreme weather events [2], which can negatively impact human health, cause infrastructure damage, etc. [3]. Thus, there has been an increase in research activity with a focus on the situation, trends, and mitigation of these events.

Among the different types of extreme events, heat wave (HW) is one case that has been extensively discussed. Generally speaking, a heat wave refers to a period of time with extremely hot weather. According to the WMO's Task Team on the Definition of Extreme Weather and Climate Events (TT-DEWCE), a heat wave should meet these conditions: (1) the weather is unusually hot and exceeds some given threshold; (2) the event lasts for at least two consecutive days; and (3) occurs during the hot period in one year [3]. In different countries or regions, the indices used to define hot, thresholds and duration varies. In China, the official definition is given by the China Meteorological Administration (CMA); a heat wave refers to a weather event with more than three consecutive days with a daily maximum temperature above 35 °C [4]. Similar to other types of extreme events, it was determined via research investigations that the probability of extreme heat has increased by ten times or more [5] and the regions affected by heat waves has grown in

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recent years [6]. In China, current research has also revealed that heat waves have increased significantly increased nationwide since the 1960s according to observational data [7], especially in the northern part of China [8].

Heat waves cause negative impacts in many aspects [5], including but not limited to mortality rate and human health [9]. In 2003, a severe heat wave in France caused more than 14,800 deaths and led to significant research activity and discussions on the cause, effects, and lessons of these events [10]. The heat wave occurred in India in 2015 caused more than 2500 human deaths [11]. In 2017, numerous significant HWs occurred around the world and 30% of the world's population was facing this extreme event [1].

The increasing occurrence of heat waves has also worsened the indoor thermal environment, which has led to a far higher incidence of mortality than otherwise [3]. In 1995, a heat wave in Chicago caused more than 700 additional deaths than normal due to medical illness in individuals who were socially isolated and without access to air conditioning [12]. During the extreme heat days in Athens in 2007, the indoor temperatures of low-income houses were 4.2 °C higher than that the temperature during normal years, and higher than 30 °C for approximately 85% of the entire hot summer period [13]. Adapting to an adverse indoor environment usually means that energy consumption related to cooling increases dramatically. The daily electricity consumption, peak load, and daily maximum outdoor air temperature show a strong correlation during the summer of Shanghai [14]. In California, the transmission and distribution (T&D) network was affected by heat waves in 2006 because of the heavy cooling load [15]. After the extreme heat wave in 2003 in Europe, the air-conditioning market boomed in France, followed by an increase in electricity demand [16].

Although the occurrence of heat waves and their impacts have been extensively studied, there have been a few studies on how heat waves affect the indoor thermal environment and the existing studies on this topic are always focusing on some past events. Those studies are meaningful and helpful to understand the phenomenon and can remind people of the importance of climate change adaptation. However, for real projects, it is needed for designers and engineers to know the situation under the event, which may not have happened yet and need to use simulation for analysis, such as energy consumption, HVAC systems and indoor thermal environment evaluation. Simulations need accurate inputs. For the impact of heat waves, the key input is the weather data representing the characteristics of the heat waves. In other words, to analyze how heat waves influence building energy use and indoor thermal environment, the first step is to generate appropriate weather data.

In some previous studies, actual weather data during one event was used. For example, Tremeac et al. used five days during the 2003 heat wave in Paris to simulate the urban heat island situation [17]. This approach can demonstrate results during one heat wave, but the representativeness of the weather data is questionable since the duration of a single heat wave event is usually less than ten days. Thus, the full effects of the previous climatic condition may not be reflected. On the other hand, the heat wave event study is to find out the worst situation in a long period of time, but the heat waves before the 2000s are not paid lots of attention and it is hard to ensure the events in recent years are the worst. Thus, it is needed to find some other methods to derive the weather input, which should be one year (or one summer) long and based on a long period of historical weather data.

There have been many studies on weather data generation for simulation use in the field of building science or heating, ventilation and air-conditioning (HVAC) [18]. Different types of typical year weather data files are for different applications using different generation methods with different kinds of data sources.

First, in terms of application, the most widely used type was the weather data reflecting the typical weather, such as the Typical Meteorological Year (TMY) [19], the Weather Year for Energy Calculations (WYEC) [20], the Chinese Standard Weather Data (CSWD) [21], and the Test Reference Year (TRY) [22], etc. The simulation results using these files are able to show the general building energy use under the climatic condition and are used for energy conservation in many countries, such as China [23] and the United States [24]. However, extreme events usually happen once in more than ten years and the main concern is not the typical situation. Thus, this kind of files is not suitable for heat wave simulation analysis.

Besides the typical year weather data, there are hot-year weather data files, such as the Design Summer Year (DSY), the near extreme Design Reference Year (DRY), and the Summer Reference Year (SRY). The DSY is used to represent near-extreme hot summers by selecting the year with the 3rd hottest daily mean dry-bulb temperature from April to September over 20 years [25]. The near extreme DRY is based on 100 simulated results of 30-year weather (3000 years in all) using the UKCP09 weather generator and then select the near extreme hot weather using different rules, such as the 99th hottest months (June to August) based on the monthly mean dry-bulb temperature [26], or the 87.5% hot year based on dry-bulb temperature, solar irradiance, and humidity [27]. The Summer Reference Year (SRY) is an adjustment of the TRY and uses the 90th warmest temperature to select the year [28]. It could be seen that compared with the typical weather data like TMYs, this kind of data can reflect the hot condition. But for heat wave events, as mentioned in some studies, near extreme weather data missing extreme values are not adequate [29].

In recent years, with the increase in extreme weather events, numerous investigations have been conducted on extreme hot weather data generation, such as the Hot Summer Year (HSY), the Extreme Meteorological Year (XMY) and the Untypical Meteorological Year (UMY). The HSY is the hottest year selected throughout the highest weighted cooling degree days (WCDH) (pHSY-1) or the most hours of high physiologically equivalent temperature (pHSY-2) [30]. The XMY is a variation of the TMY to include the hottest summer [31] and another type of XMY selects the extreme months with the highest values of climatic variables [32]. The UMY uses the WYEC2 construction methods, while the indices are changed to the maximum and minimum of the dry-bulb temperature, daily solar radiation and maximum wind speed to reflect the extreme weather [33]. All these weather data select the year with the most serious event so as to reflect the impacts of the extreme events.

The weather data generation methods vary in two aspects. The first is to select one entire year (or one summer and winter) or to select twelve individual months and combine them as one entire year. The former includes the TRY, the DRY and the SRY, while the latter includes the TMY, the CSWD and the WYEC. The second aspect is the parameters used to determine the selected object. Some methods use weighted indices with different meteorological parameters including temperature, humidity, solar radiance, wind speed, etc., while others use only one parameter, for example, the DSY uses the daily mean dry-bulb temperature in the original file and the weighted cooling degree hours in updated research [34].

In terms of data source, in most studies, historical weather data is used. While the trend of heat waves has increased significantly in recent years, some studies considered the use of simulated future weather data instead of the historical years [35] to generate heat wave weather data. The length of historical data is also discussed. For example, the 20-year period is used in some methods for selecting the extreme weather events, but is considered not long enough to include the year with extreme weather events in some studies [36].

Above all, it could be seen that there have been many studies focusing on extreme weather data generation and different types of weather data files have different considerations on the generation methodology. However, all the existing methodologies are directly based on the outdoor weather parameters. But it is the indoor thermal environment that people are really concerned about during heat waves in most cases. Various weather parameters, e.g., outdoor dry-bulb temperature, humidity, solar irradiance, and wind speed and direction,

have different impacts on the indoor thermal environment and all affect the indoor overheat. Moreover, the impact of heat waves is not only determined by the weather, but also by the internal heat gains and building performance. In other words, the impact of heat waves on the indoor thermal environment is a complex and integrated system effect based on outdoor weather conditions as well as building characteristics that cannot be simplified as driven purely by outdoor weather parameters. As a result, most investigations which only focused on outdoor weather data may not accurately characterize the impact of heat waves and additional studies that focus on the indoor environment instead of just the outdoor situation are needed. Therefore, we propose a method to generate heat wave weather data based on their impacts on the indoor thermal environment which considers the building dynamic performance as well as outdoor weather conditions.

Based on the above considerations, this study intends to address the highlighted knowledge gaps in the context of China due to weather data availability, although the methodology applies to other countries or regions. The main research problems to be addressed include: (1) How to evaluate indoor thermal environment during heat waves? (2) What is the summer indoor thermal environment without cooling over the past years with different climate conditions? (3) How to obtain typical heat wave weather data for further studies? In this study, we focus on the residential sector based on the assumptions that there are homes (e.g., disadvantaged communities, low-income housing) without air-conditioning, or homes where the occupants cannot afford to operate air conditioning during heat waves due to peak electricity pricing or electric grid outage or blackout. This study focuses on heat waves but the methodology also applies to cold waves, which is part of our future studies.

2. Methodology

2.1. Overview

In order to understand the effect of heat waves on the indoor thermal environment in China's residential sector, the indoor temperature without cooling in a typical residential building (apartment unit) was initially simulated using the historical actual weather data in several typical cities. The building performance and the occupant behavior reflect the real situation of China's households and the chosen cities reflect the different climate conditions in China.

Secondly, indoor thermal simulation results are used to analyze the indoor situation during hot summers. The required definitions and indices are defined first, then they are used to evaluate the indoor and outdoor environment across multiple years. To understand whether the impact of the heat wave is sensitive to the efficiency levels of a building, three types of building envelopes are studied which represent the old, current, and expected future building energy codes.

Finally, the typical hot year (THY) weather data is selected based on their impact on the indoor thermal environment. The THYs for selected cities were generated from the statistics of the indoor thermal environment simulation results. The application of the THY weather data and the limitation of this study are also discussed.

The overall methodology is represented in Fig. 1.

2.2. Definition and indices

Although numerous studies have been conducted with a focus on heat waves, the analysis of the effect of the indoor environment is still rare. In different reported studies, the definition of heat waves and the indices used to evaluate the impact of a heat wave on the thermal environment are different. Thus, it is necessary to choose suitable definitions and indices based on the research objective. The key problems include: (1) the definition of heat wave used in this study; (2) the index used to represent the heat wave characteristics; (3) the type and threshold of the index to determine if the indoor thermal environment is hot; and (4) the data resolution of the indices.

Two types of heat waves, namely, the absolute heat wave (AHW) and the relative heat wave (RHW), are discussed in existing studies. The former is defined depending on the absolute value, e.g., counting the number of days with a (daily average or maximum) (outdoor or indoor) temperature above a threshold value (such as 35 °C or 100°F); while the latter is dependent on the relative threshold [37], e.g., counting the number of days that are hotter than a certain (like 85th or 90th) percentile of days in the period. In this study, although the learning objective is the indoor overheat, the AHW was chosen and the absolute value was used to evaluate the thermal environment.

Heat wave indices can be divided into two types, one for the overall situation and the other for the most severe events in one year. In addition, for residential buildings, since most people sleep at their homes in the usual case, hot nights may significantly affect sleep quality [38]. This is particularly the case for the elderly [39], thus the temperature during sleeping hours is also worthy of consideration. Therefore, the situation of hot nights is included. In terms of parameter types, the indices mainly include the number, frequency, duration, intensity [7], and magnitude [37] of heat waves, representing the quality and quantity of the heat wave events based on different aspects. Combining these two terms, there are dozens of indices that can be used. In this study, in order to gain a complete understanding of the heat wave situation, three indices including the overall intensity, the wave with the highest intensity or longest duration, and the number of hot nights were chosen.

In current investigations, there are primarily three kinds of indices used to evaluate the indoor thermal environment. The first, also the most widely used and simplest index is the indoor dry-bulb air temperature. The boundary line of overheat may be from 25 to 33 °C for different guidelines or studies, referring to the maximum, average, or the degree-hour of the daily or hourly temperature [3]. Although humidity, solar radiance, and other parameters also affect the human thermal sensation, some researches take them into consideration, which forms the second type of index, including the Heat Index (HI) and the wet-bulb globe temperature (WBGT) [3]. The third type is the index based on the thermal comfort theory, such as the PMV or the PPD indices [40]. The last two indices reflect the human thermal comfort more comprehensively, but are also more complex and need more inputs for calculation. As an initial attempt of the study to focus on the indoor overheat, the simplest and most direct index of the indoor dry-bulb temperature could be used. The upper line of the outdoor air temperature was set to be 35 °C which is the same as the definition by CMA. For indoor air temperature, as there is no universal definition of indoor overheat in residential buildings, the thermal comfort analysis results were used. According to Zhang et al.'s indoor thermal comfort research, 31.5 °C is the widely accepted temperature threshold in China [41]. In this study, this temperature is used as the upper threshold of indoor air temperature. Another aspect is required to define the hot nights. In this research, the daily minimum temperature was used as this index. Since there are few studies that focus on the night temperature, in this study, the line was set as 26.7 °C for both indoor and outdoor according to existing studies [42].

The data resolution is another problem which needs to be discussed because of the gap between the outdoor weather and indoor environment studies. In most investigations on outdoor heat waves, daily data is used. However, for the indoor situation, hourly data is used in many cases, including the researches on indoor thermal environment [43]) and occupational hazards at workplaces [44]. In this study, since the establishment of the relationship between the outdoor and indoor environment is one of our goals, both resolutions were used. Meanwhile, in existing studies, heat waves refer to extreme hot weather lasting for three or more days; Thus, in this study, although the daily situation is discussed, hot days lasting less than 3 days are not taken into consideration. However, for the hourly situation, all hot hours are included.

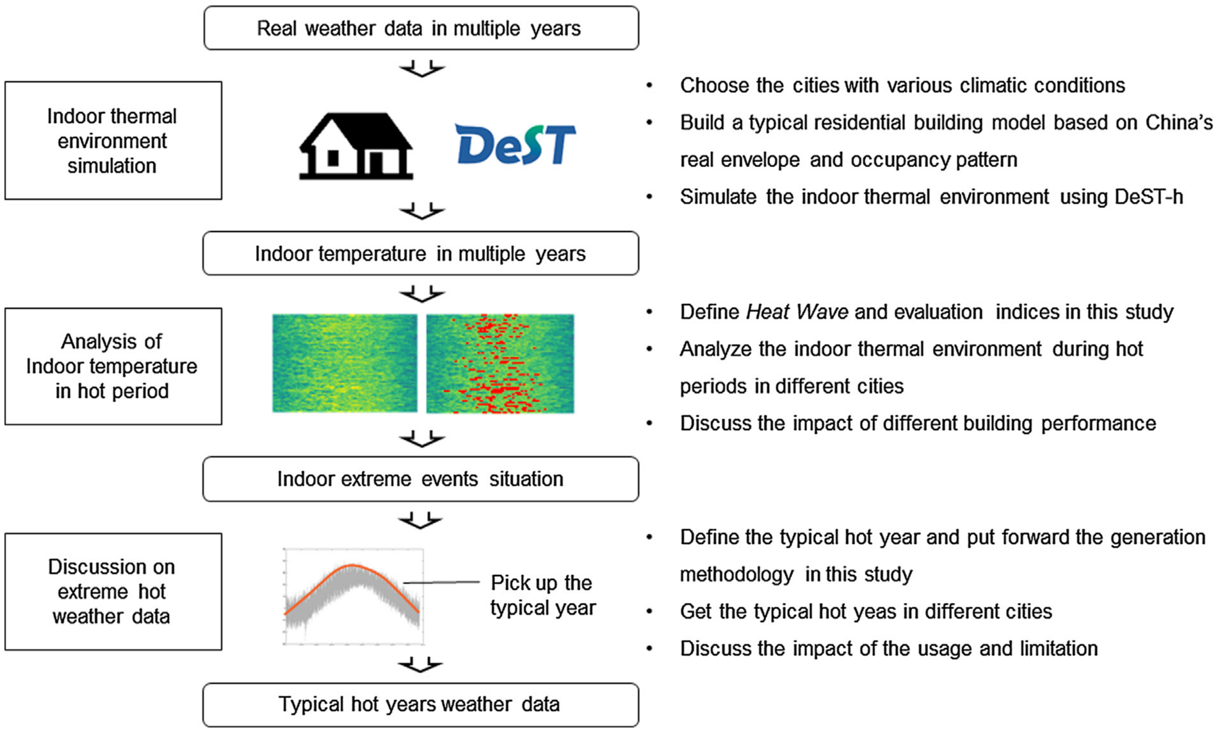


Fig. 1. Overall methodology to evaluate and select the typical hot year weather data.

In total seven indices were used in this research to evaluate the heat wave situation from different aspects:

(1) Total heat wave intensity using hourly data in one year (*HWI_hr*): the sum of the degree hours when the temperature is above the upper line, calculated using formula (1):

$$HWI\_hr = \sum_{allhour} (T_{hr} - T_l) \tag{1}$$

$$T_{hr} - T_l > 0$$

where T_{hr} is the indoor or outdoor air temperature and T_l the upper line of the accepted temperature. In this study, it is 31.5 °C for indoor and 35 °C for outdoor.

(2) Maximum of the heat wave intensity for each event in one year using hourly data (*MHW_hr*);
(3) Duration of the longest heat wave in one year using hourly data (*LHW_hr*): the maximum hours when the temperature is higher than the upper line;
(4) Total heat wave intensity using daily data in one year (*HWI_d*): the sum of the degree days when the daily maximum temperature is above the upper line;
(5) Maximum of the heat wave intensity for each event in one year using the daily data (*MHW_d*);
(6) Duration of the longest heat wave in one year the using daily data (*LHW_d*): the maximum days when the maximum temperature is higher than the upper line;
(7) Number of hot nights in one year (*HNN*): the number of days with a minimum daily temperature that is higher than the line. The upper line for this index is 26.7 °C.

In the following sections, all these indices will be calculated using real weather data and simulated indoor temperature in different cities. Based on these indices, the situation for the indoor thermal environment during extreme events will be analyzed.

2.3. Weather data

In this research, the historical weather data is used as the simulation input to analyze the indoor thermal situation during hot summers and to generate the typical weather data, since the actual data are able to simulate the real situation and affect the actual events [45]. In contemporary studies, a period of 30 years is widely used as the span to generate typical weather data [18]. Although extreme weather does not occur frequently, the period of historical data should be reconsidered. In this study, according to the data accessibility and the related research on climatic cycles, a period of 60 years, from 1955 to 2014 was chosen as the time span to reflect climate trends [46].

In most cities in China, meteorological were acquired every 6 h before 2004, and hourly after 2004. Since hourly weather data is needed in building thermal performance simulation, the first step was to generate the hourly data according to the observed records for the years from 1955 to 2004. In this study, the method to generate hourly data for the CSWD was used [47]. The generated results including all the essential weather parameters would be used for the thermal performance simulation.

Given its vastness, the climate characteristics of different cities in China can vary significantly. In *the Code for Thermal Design of Civil Building* published in 2016 (GB 50176-2016), five major climate zones, namely, the severe cold zone (SCZ), the cold zone (CZ), the hot summer and cold winter zone (HSCWZ), the hot summer and warm winter zone (HSWWZ), and the temperate zone (TZ), as well as eleven subzones were established with different building performance and HVAC system design requirements [48]. Since solar radiance also affects heat, the distribution of solar energy is also taken into consideration according to the solar energy resource distribution zones. Zone I refer to the zone with the most abundant solar energy and zone IV the least [49]. In this study, 12 cities were chosen to represent different climate situations in China. The rules used to select the cities included three aspects: (1) in each combination of climate zone and solar energy zone, at least one city needs to be chosen unless there are many cities; (2) in each combination, when there are some obvious gaps with respect to the average temperature in the hottest month (ATHM) and CDD 26, more than one

Fig. 2. Geographic location of the 12 selected cities.

Table 1
Basic weather information of the 12 selected cities.

	City	Province	Climate zone	Solar zone	ATHM (°C)	CDD 26 (°C·d)	Latitude (°)	Longitude (°)	Elevation (m)
1	Harbin	Heilongjiang	SCZ (B)	III	23.8	14	45.9	126.6	118.3
2	Urumqi	Xinjiang	SCZ (C)	II	23.7	36	43.8	87.7	935
3	Lhasa	Tibet	SZ (A)	I	15.7	0	29.7	91.1	3648.9
4	Yinchuan	Ningxia	SZ (A)	II	23.9	11	38.5	106.2	1110.9
5	Beijing	Beijing	SZ (B)	II	27.1	94	39.8	116.5	31.3
6	Zhengzhou	Henan	SZ (B)	III	27.2	125	34.7	113.7	110.4
7	Shanghai	Shanghai	HSCWZ (A)	III	28.5	199	31.2	121.4	4.6
8	Wuhan	Hubei	HSCWZ (A)	III	29.6	283	30.6	114.1	23.6
9	Chongqing	Chongqing	HSCWZ (B)	IV	28.4	217	30.8	108.4	186.7
10	Guangzhou	Guangdong	HSWWZ (B)	III	28.8	313	23.2	113.5	70.7
11	Haikou	Hainan	HSWWZ (B)	III	29.1	427	20.0	110.3	63.5
12	Kunming	Yunnan	TZ (A)	II	20.3	0	25.0	102.7	1888.1

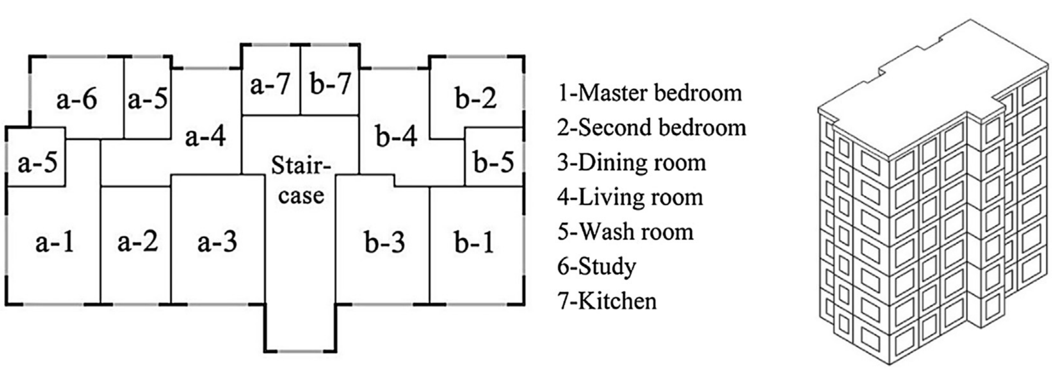


Fig. 3. The layout of a typical apartment building in China.

city is chosen; and (3) the weather data of the city are available from 1955 to 2014, which means that the weather station retained the completed and continuous observed data over 60 years. Fig. 2 shows the geographic location of the cities while Table 1 shows the basic weather information.

2.4. Typical residential buildings

In order to simulate the indoor thermal environment, a typical residential building (apartment) model was set up for indoor thermal simulations. According to the urban household energy consumption survey (UHECS) in China which was performed in 2015 by the Building

Table 2
The building envelope characteristics in different cities.

City	U-value ($W/m^2 K$)			Window SHGC
	Roof	Wall	Window	
Harbin	0.30	0.45	1.9	0.59
Urumqi	0.40	0.50	2.0	0.59
Lhasa/Yinchuan	0.45	0.60	2.5	0.59
Beijing/Zhengzhou	0.45	0.60	2.5	0.45
Shanghai/Wuhan/Chongqing	0.8	1.0	3.2	0.40
Guangzhou/Haikou	0.9	1.5	3.5	0.20
Kunming	1.2	1.8	3.2	0.40

Energy Research Center of Tsinghua University (THUBERC) [50], nuclear families (defined as a family with two parents and one or two kids) are the main family structure in China, while the floor area per household varies from 70 to 120 m^2; and more than half of all families lived in low-rise buildings with less than eight floors [51]. In this study, the typical building is based on a real apartment in Shanghai built in 2010 [52]. The building has seven floors and two households on each floor, with a floor area of 113.5 m^2 (household a) and 85 m^2 (household b). The shape coefficient (total surface area/volume of the building) of the building was 0.33 and the combined window-wall-ratio was 0.31. The layout of the building is shown in Fig. 3. Two adults and one child live in each household.

The building envelope performance was set to comply with the current national standards for energy savings of residential buildings, or the so-called 65% of energy-efficient buildings standards in SCZ & CZ [53], HSCWZ [54] and HSWWZ [55]. Since there is no national code for the temperate zone, in this study, the city is set to follow the local standard [56]. The solar heat gain coefficient (SHGC) values are not required for the severe cold and cold (A) zones in this standard, and the values are set as normal triple pane windows. Table 2 shows the U-values of the roof, wall, and window, as well as the window SHGC values in the selected cities.

The ventilation rate will change with different window states. When the windows are open, the max ventilation rate was set to five air changes per hour (ACH) according to the existing measurements [57]). When the windows are closed, the ventilation rate is 1 ACH in the HSCW [54], HSWW and the temperate zones [55]; and 0.5 ACH in the SC and cold zones [53] according to China's design standards.

2.5. Behavior of window opening

The opening of windows significantly affects the indoor environment during summer. And when cooling equipment is not used, opening window will be an important way for indoor thermal environment adaptation when the outdoor is cooler as the cool outdoor air will help reduce the indoor temperature.

In China, it is habitual for most households to open windows when temperatures are elevated [58]. From 2013 to 2015, the authors' group had conducted serious of large-scale household surveys on occupant behavior nationwide, which include the window opening behavior [59]. The survey results show that more than 90% of families had the habit to open windows in summer, and opening window because of feeling hot is one of the main reasons (other reasons including getting up, entering the room, feeling smelly, etc.). In some cities, about half of families will open the windows all day long during summer. According to the questionnaire results, people living in the HSCW zone open windows relatively more frequently but people in other regions also have this habitat [60].

In this study, the behavior of window opening is set that occupants will open windows when the outdoor air temperature is lower than the indoor air temperature, which is in accordance with the survey results.

2.6. Building performance simulation

The Design Simulation Toolkits for residential building (DeST-h) was used as the simulation engine in this research. DeST is a whole-building energy modeling program based on state-space multi-zone heat balance method and DeST-h is the version dedicated to residential buildings [61]. DeST passed the simulation test cases defined in ASHRAE Standard 140 [62].

Since the occupant behavior of opening windows is an important factor that influences the indoor thermal environment, it is also needed to simulate the window operation. In this study, behavioral models embedded in DeST-h are used [63]. For each time step, first, the occupant's movement was simulated, which can determine the number of people in each room; secondly, the window open/close state was determined based on the occupancy state at this moment and the indoor thermal environment at last moment for each room – i.e., if the room is not empty and the indoor temperature is higher than the outdoor, the window should be opened; finally, the indoor environment was calculated according to the occupancy and the window state. In most existing simulation analyses, one hour is usually used as the time step; but in this study, it is assumed that people feel the indoor environment and react much quickly, thus the simulation time step was changed to ten minutes to ensure reasonable results [64].

3. Results

3.1. Indoor thermal environment in different cities across 60 years

It was possible to analyze the simulation results of the indoor thermal environment with real weather data over a period of 60 years in 12 cities. Although the building performance and occupant patterns stay the same in all cases in one city, the change of the temperature can be considered to be caused entirely by climate change.

Figs. 4–6 show the average indoor temperature during summer, average daily range, and summer maximum temperature over 60 years in different cities.

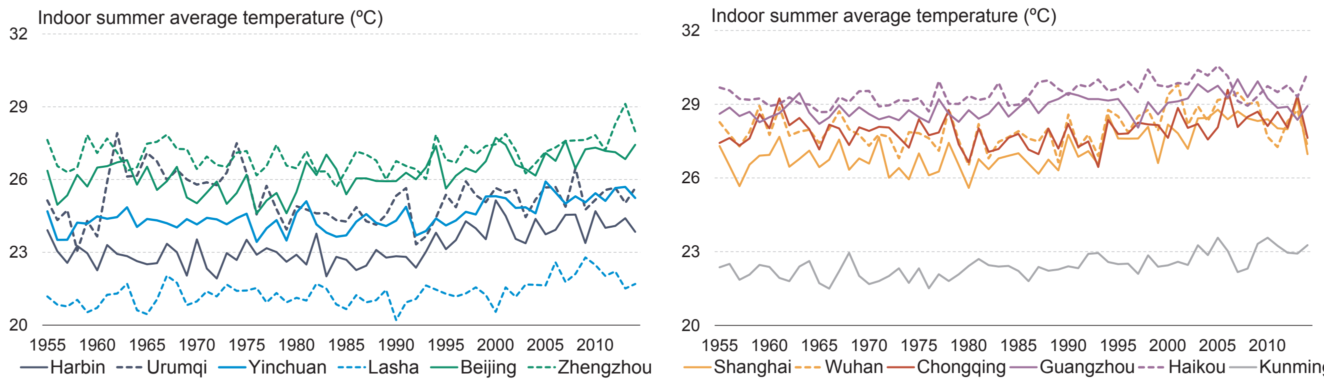
Over the time scale, it could be seen that for all cities except Urumqi, the summer average temperature and maximum temperature are on the rise, showing the effect of climate change. Among the 12 cities, Shanghai, Harbin, and Beijing are the cities with the highest regression coefficient for average temperature, while Shanghai, Yinchuan, and Beijing had the highest values for the maximum temperature. Except for global climate change, urbanization [65] and urban heat island [66] may also contribute to the rising trend.

The cities in different climate zones with different solar resource vary significantly. Thus, for the studies performed in the next step, the need for several cities with different solar radiance and CDD values may still be essential. Between climate zones, it was determined that although the average temperature of cities in HSWW zones (Guangzhou and Haikou) is higher than those in HSCW zones (Shanghai, Wuhan and Chongqing), the daily range is smaller and the maximum temperature is lower.

Compared with the outdoor situation, it could be seen that the average indoor temperature is higher and the daily range is smaller, as shown in Fig. 7. It could also be determined that the gaps in the indoor environment in different cities and years are smaller than those of the outdoor.

3.2. Indoor heat wave situation in last 60 years

Considering the indoor environment, the heat wave situation can be analyzed using the indices defined in this study. Using our definition, it is determined that there was no heat wave in Kunming and Lhasa in the simulated 60 years. Therefore, these two cities are not included in the following analysis. In addition, it was determined that among the seven indices defined, several indices, namely *HWI_hr* and *HWI_d*, *MHW_hr*



a) SCZ and CZ

b) HSCWZ, HSWWZ and TZ

Fig. 4. The indoor summer average temperature in 60 years.

and *LHW_hr*, are highly correlated, as shown in Fig. 8. The outdoor data also show similar trends. Thus, in the following parts, only five indices were used, namely, *HWI_hr*, *MHW_hr*, *MHW_d*, *LHW_d* and *HNN*.

Fig. 9 shows the indoor heat wave intensity in selected cities across 60 years. Depending on the trends, the ten cities can be divided into three groups: Group 1 includes Harbin, Yinchuan, Beijing, Shanghai, Guangzhou, and Haikou, whose *HWI_hr* values are on the rise over the 60-years period, Group 2 includes Zhengzhou, Wuhan and Chongqing, whose *HWI_hr* values decreased in the first 30 years and increased in the latter, and Group 3 includes only Urumqi, whose *HWI_hr* values declined over the 60 years. These differences may be caused by climatic cycles, climate change and heat island effect.

It could be seen that although the cities in the HSWW zone, such as Guangzhou and Haikou, are always considered quite hot, the heat wave intensity is actually less than the cities in the HSCW zone such as Shanghai, Wuhan and Chongqing. Through further analysis, it is found that although the average temperatures in the HSWWZ cities are higher, the average daily ranges are lower and the maximum daily temperatures are higher, as shown in Figs. 4–6. Fig. 10 shows the indoor and outdoor daily maximum temperature distribution in Shanghai and Guangzhou. It could be seen the outdoor and indoor distributions show similar trends: although the HSWW zone is hotter, the number of extremely hot days is lower than the HSCW zone, and the heat wave indices are also relatively lower.

Figs. 11–13 show the results of the indices reflecting the most serious heat wave in one year over the 60-year period among the 10 cities. It could be seen that using different indices, the results vary significantly. Most years with quite severe hot events are in the last 10 years or around the 1960s. In the simulated 60 years, the heat waves with the highest intensity occurred in Shanghai in 2013 while the longest events were in 1975 for Chongqing and 1967 for Shanghai.

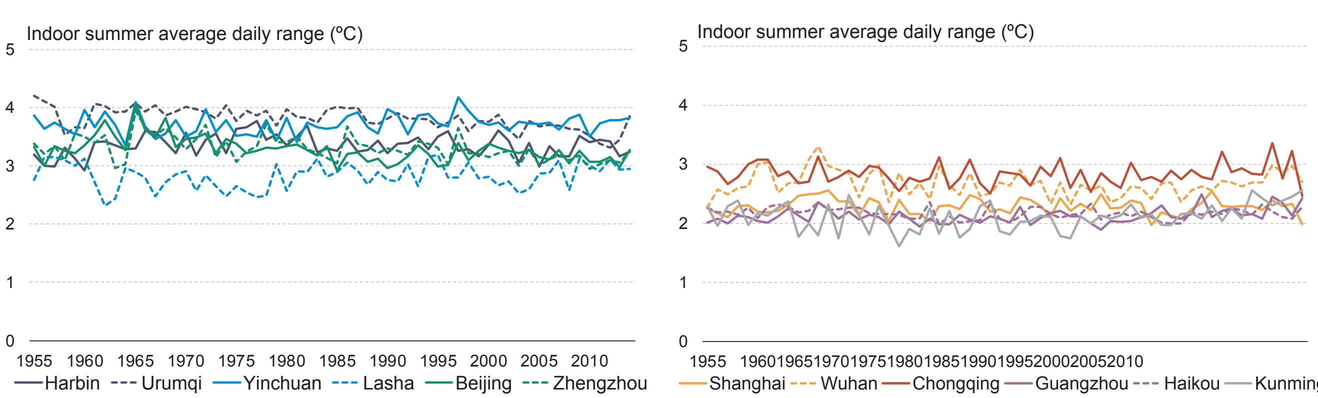
Examining the most severe events in each city, it could be seen that the situation in Beijing and Zhengzhou may be even more serious than that in Guangzhou and Haikou, as represented in Fig. 14. Thus, in some sense, the indoor heat wave situation may require a greater focus on the cold climate zone instead of southern China, where the summer is hot. The reason may be related to the building performance because thermal inertia and envelope insulation of the buildings in CZ is stronger since heating demand is the main factor considered in the thermal design in this climate zone.

Fig. 15 shows the number of hot nights over the 60-year period for 10 cities. Compared with other traditional heat wave indices, this index reflects the unique characteristics of residential buildings. In HSCWZ, the years with severe events may have more than 30 hot nights, which would lead to a significant health problem in the human population.

Comparing the indoor and outdoor events, the indoor trend is determined to be similar to the outdoor trend after a sufficiently long period of time, but there are also differences observed for some years. Fig. 16 shows an example of indoor and outdoor temperature using Shanghai's 2013 weather data. It can be seen that in some cases, the outdoor temperature decreases over a short time and breaks the heat wave, but the indoor temperature decreases much slower, which causes the heat waves to last longer.

3.3. Heat waves with different envelope performance

Since the built environment is not only affected by outdoor weather, the building envelope and occupancy behavior should also be taken



a) SCZ and CZ

b) HSCWZ, HSWWZ and TZ

Fig. 5. The indoor summer average daily range in 60 years.

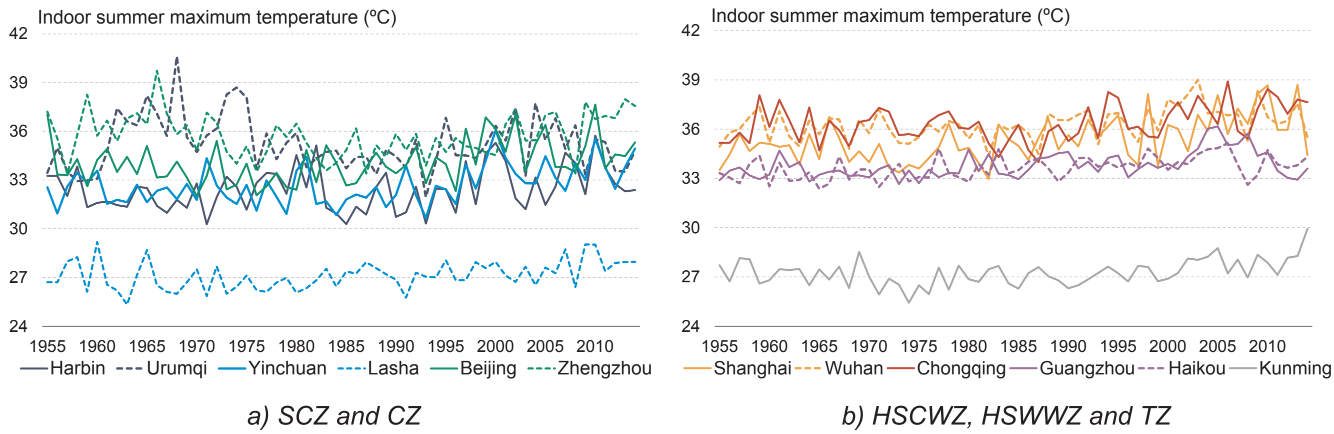


Fig. 6. The maximum indoor temperature during summer over a 60-year period.

into consideration. Although the objective of this research was to identify the most severe years, the worst situation with respect to behavior would entail being at home for the entire day, namely, the room with the highest temperature at any time should be included, which was the case for contemporary investigations. Therefore, in this part, only the impact of different envelopes is discussed.

The existing studies show that in different climate zones in China, the approaches for improving building performance and the corresponding energy consumption [67], as well as the influences due to climate change, including energy consumption [68] and design loads [69], were different. For heat waves, most studies focused on one city or region and the results varied. Some studies showed that well-insulated buildings were hotter during extreme events [70], while others determined that old buildings were more dangerous, which could be attributed to different climatic conditions [71]. In this study, buildings with three levels of envelope performance in four cities were simulated to ascertain if different levels of insulation would change the overheat situation, as shown in Table 3. The second envelope performance complies with the current national standard, while the first was mainly based on the 50%-saving energy efficient standards. The third was based on the 75%-saving standards.

Fig. 17 shows the simulation results of the distribution of the indoor temperature with different envelopes in the four cities and Fig. 18 shows the results of heat wave intensity.

It could be seen that the building envelope performance does not seem to have significant effects on the indoor thermal environment, including the indoor temperature and heat wave situation, which seems in contrary to common sense. Through deep analysis, the main reason for such results could be the occupant's habitat of opening windows. In usual cases, buildings with better insulation and less ventilation rate can reduce the heat exchange between the indoor and outdoor. But in this study, the occupants tend to open windows when indoor temperatures were elevated, which enhances the heat exchange from outdoor and weakens the effect of building envelopes. In other words, for the buildings where people have the habitat to open windows, it is not effective to improve insulation or ventilation rate to mitigate the effects of heat waves.

In addition, the exterior shading, building shape, etc. can also change envelope performance but are not included in this study. These factors may have great impacts on the indoor environment when windows are opened and may be the potential of envelope improvement in next decades.

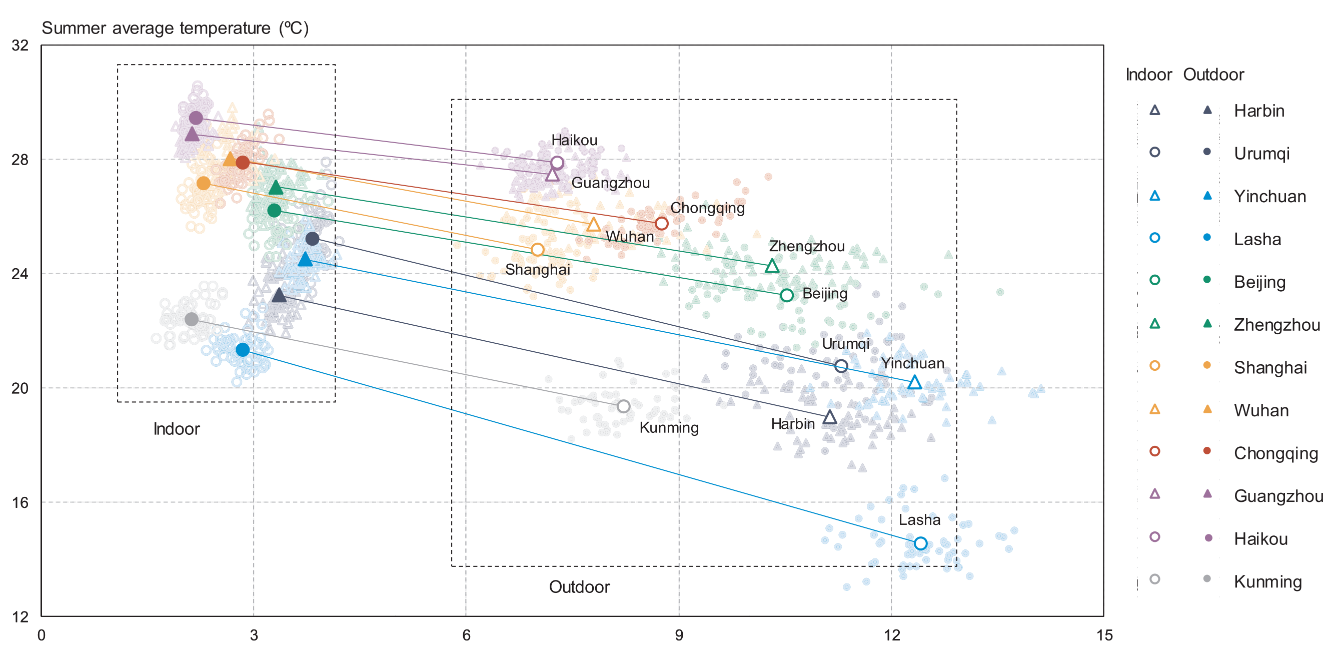


Fig. 7. The average temperature and average daily range of indoor and outdoor.

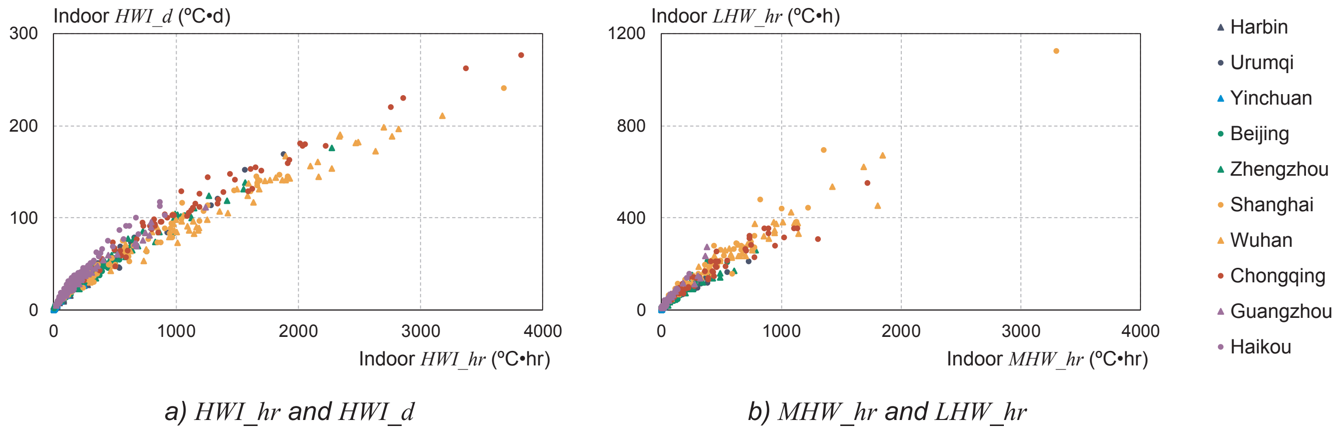


Fig. 8. The correlation of indoor heat wave indices.

4. Discussion on typical hot year weather data

4.1. THYs generation in each city

In this study, a new kind of weather data, the typical hot year (THY) was proposed which focuses on the impact of heat waves on the indoor thermal environment. The THY represents the most severe impact of extreme events, which is selected from the historical 60 years that results in the hottest indoor thermal environment based on the defined indices. Although indices are calculated using only the indoor dry-bulb temperature, the simulation process takes the other climate parameters into consideration so that the indoor temperature can reflect the thermal environment.

In existing studies, the weather data may be generated by selecting one entire year or combining twelve selected individual months. For extreme events, each extreme month may not happen in the same year and a year combining twelve extreme months is less likely to happen. Thus, selecting the worst year seems more reasonable, which is adopted in this study to select the THY. In order to reflect overheating during different aspects, three THYs are further defined: THY-I for the year selected based on the largest annual total intensity of overheat, THY- E for the year selected based on the maximum of the annual weighted sum of the largest intensity and the longest duration of overheat event, and THY-N for the year with the largest number of hot nights. Each specific annual period corresponds to the matched indices: THY-I for *HWI_hr* and *HWI_d;* THY- E for *MHW_hr*, *LHW_hr*, *MHW_d;* and *LHW_d*, and THY-N for *HNN*. The concrete steps for the generation of THYs are:

(1) Use min and max values to normalize each index according to formula (2):

$$I^* = \frac{I - I_{min}}{I_{max} - I_{min}} \tag{2}$$

where I^* is the normalized value, I is the original value of each index.

(2) Use the weighted summation (formula (3)) to obtain the value matching each kind of THY in every year; the weight is 0.5 for each index for THY-I and 0.25 for each case for THY-E. In the calculation for THY-N, this step can be skipped since there is only one index;

$$X = \sum_j w_j I_j^* \tag{3}$$

where X is the value for each THY in different years and w_j is the weight of each index.

(3) Select the year with the highest value for each THY definition for each city. If the highest value occurs in two years, another index will be used for the second step selection. *HWI-hr* is used for THY-I, the average of the normalized value of *MHW_hr* and *MHW_d* for THY-E, and a new index, *HNI*, is defined for THY-N, which represents the intensity of the hot nights using formula Eq. (4):

$$HNI = \sum_{allday} (T_{d\_min} - T_l) \quad T_{d\_min} - T_l > 0 \tag{4}$$

where T_{d_min} is the minimum indoor daily temperature and T_l the upper

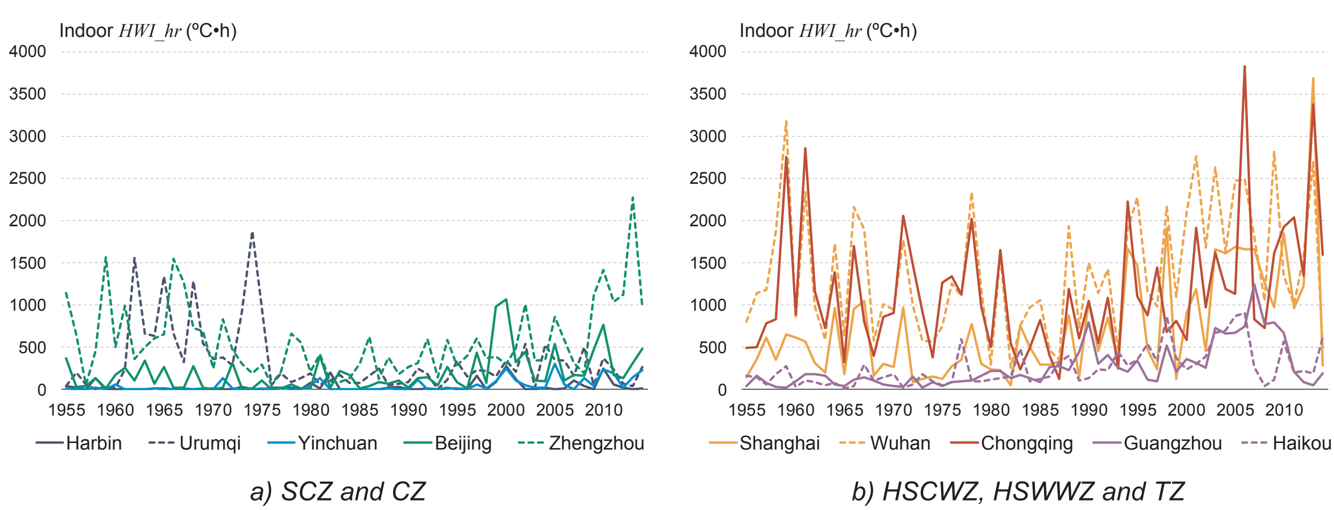


Fig. 9. The indoor heat wave intensity (HWI_hr) over 60 years.

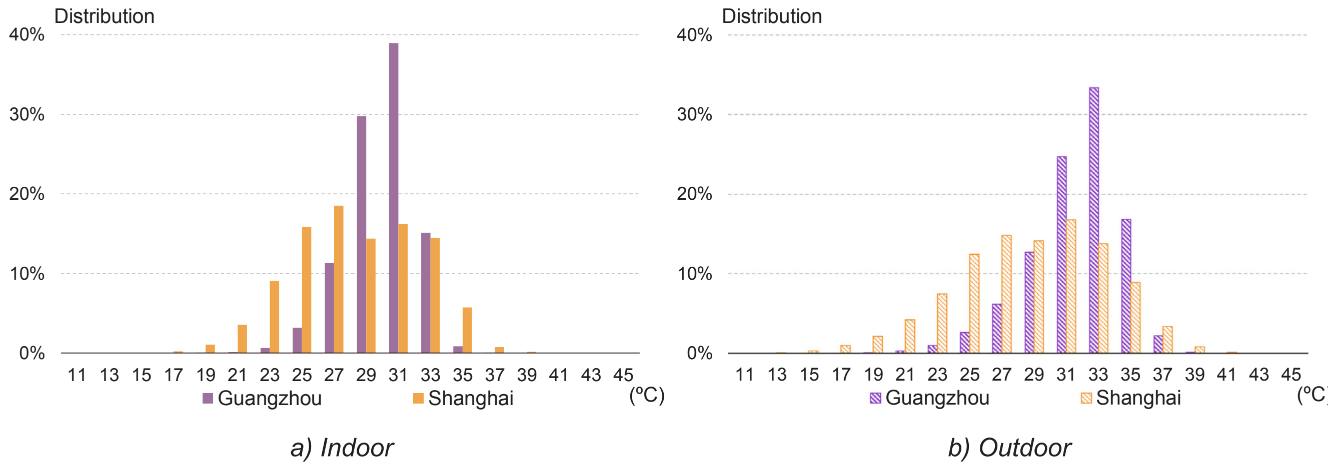


Fig. 10. The indoor and outdoor daily maximum temperature in Guangzhou and Shanghai.

line, which is 26.7 °C.

Using this method, the THYs of different cities can be determined, as shown in Table 4. Since there are no heat wave events in Lhasa or Kunming, these two cities are excluded. In this study, after the first round of selection, the THY-N in Beijing and Haikou show up in two years and the second index is used to determine the year.

It could be seen that in some cities, such as Harbin, Urumqi, Zhengzhou, Shanghai and Guangzhou, the year with the highest value using different definitions is the same; while in other cities like Chongqing, they are all different. Although the duration for selecting typical weather data is 30 years in most studies, a longer duration is required for extreme events since the selected years are before 1985 in some cities.

Based on a comparison of the THYs using the indoor and outdoor temperature in Table 4, it could also be seen that in many cases, the results are different. Thus, for the studies that focus on the indoor environment, using the indoor data to evaluate or analyze heat wave impact is more appropriate.

For different levels of building envelope performance, it was determined that in this study, while the indoor environment did not differ significantly for different envelope settings include insulation and ventilation rate, the THYs correspond to the same year in most cases. As previously mentioned, this may be caused by the opening of windows when temperatures are elevated, which lessens the impact of the building envelope insulation. If the envelope settings and behavior patterns changed, the results might also differ.

4.2. Applications and limitations

Compared to the traditional generation methods using the outdoor temperature, the THYs in this study are able to directly represent the indoor thermal environment. Thus, for the studies focusing on the indoor situation, as an important part of resilience to climate change, the use of the THYs generated in this study prevails.

Firstly, since individuals usually stay in residential buildings for a long time, the indoor thermal environment will significantly influence health and mortality and the indoor overheat will be an important factor. The THYs can be used to simulate the extreme indoor situation and help to better evaluate the heat wave effects. In this study, THY-I can be used for the situation during a given summer period, THY-E for the most severe event, and THY-N for specially required evaluation of sleeping effects. For example, the THYs can be used for passive design to simulate the indoor environment during extreme heat events, which is important for occupants but unfortunately ignored in most existing projects [72].

Secondly, hot indoor rooms will increase cooling demands. Thus, an extreme event will cause a significant increase in cooling energy consumption. The THYs, especially THY-Es, can be used to simulate the peak demand in cooling loads or electricity consumption during the most severe heat wave. In addition, since power plant generation capacity is also affected by extreme heat [73], the combined simulation of the demand and supply sides will also be a challenge, and the THYs can be used as an input to help HVAC engineers [18] and power station

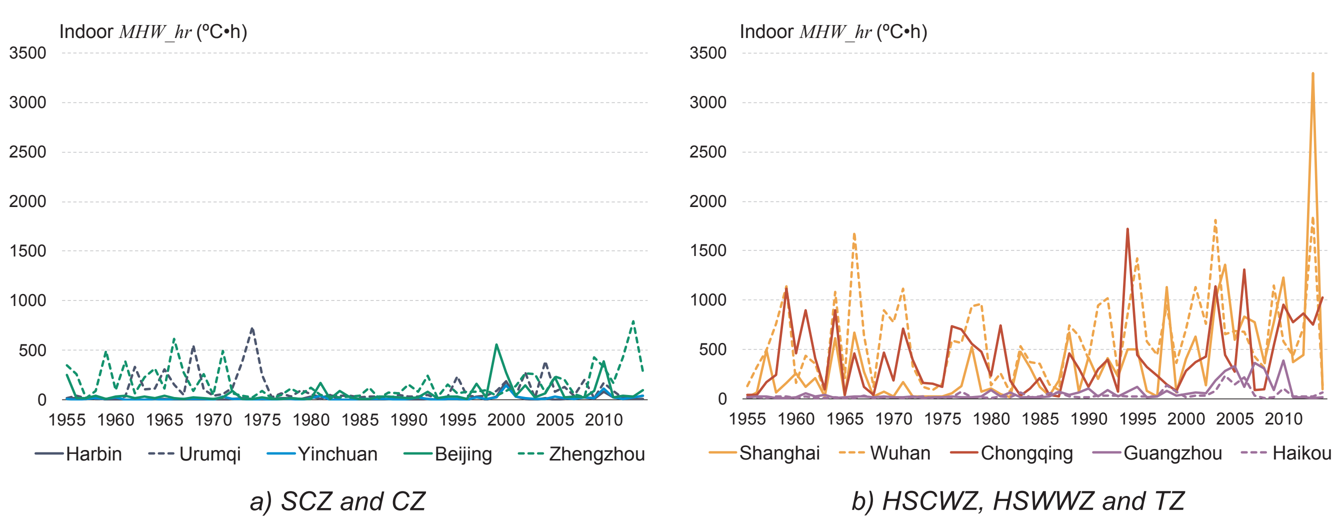


Fig. 11. The maximum indoor heat wave intensity using the hourly data (MHW_hr) over 60 years.

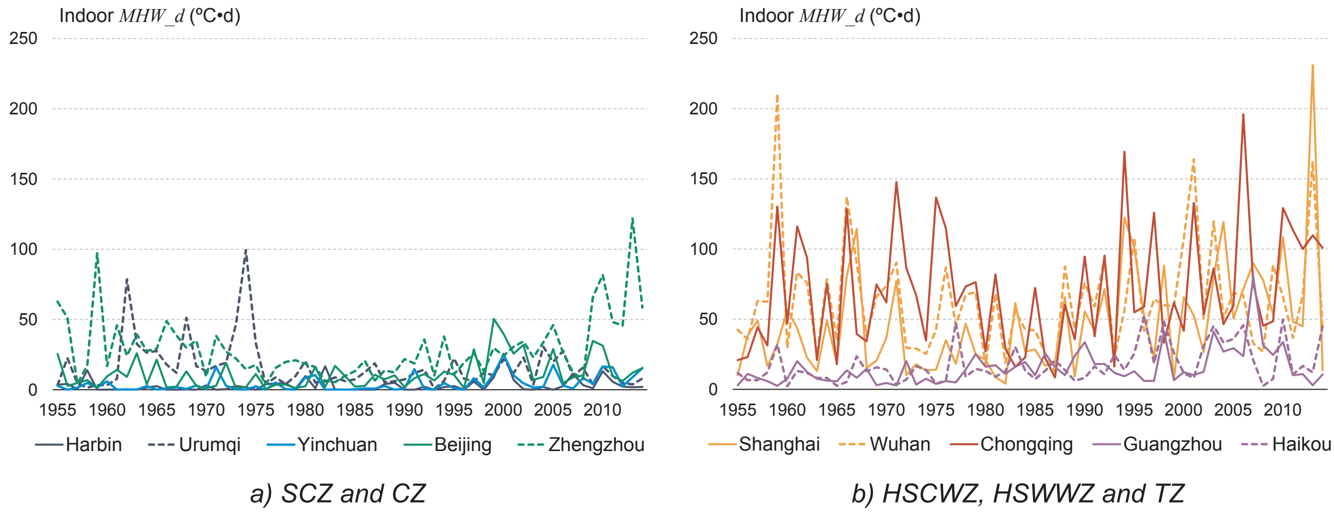


Fig. 12. The maximum indoor heat wave intensity using the daily data (MHW_d) in 60 years.

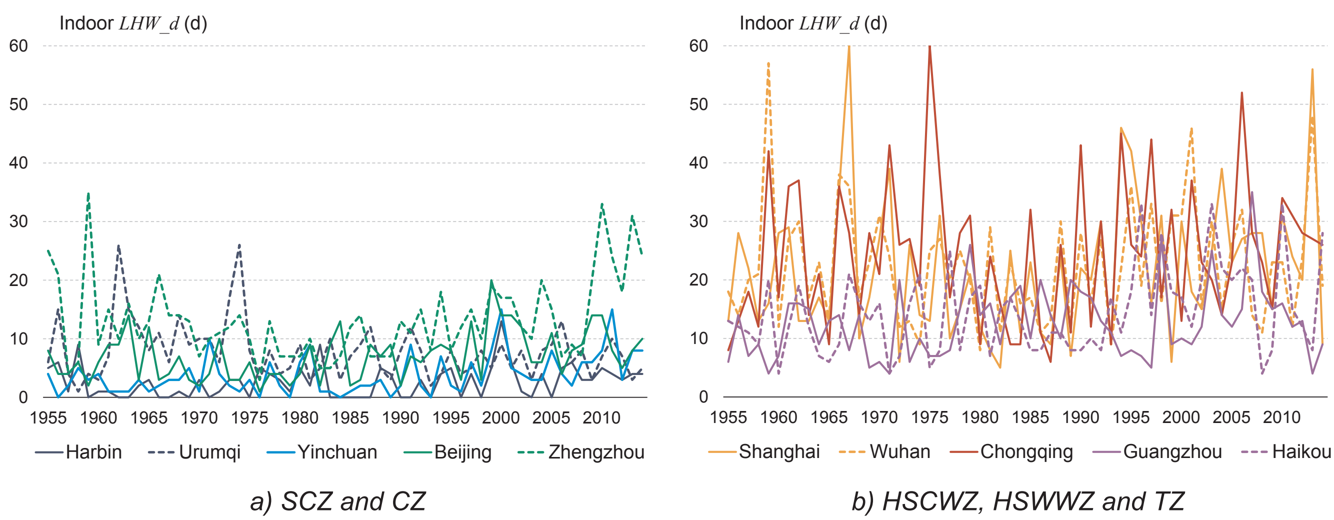


Fig. 13. The longest indoor heat wave using the daily data (LHW_d) over 60 years.

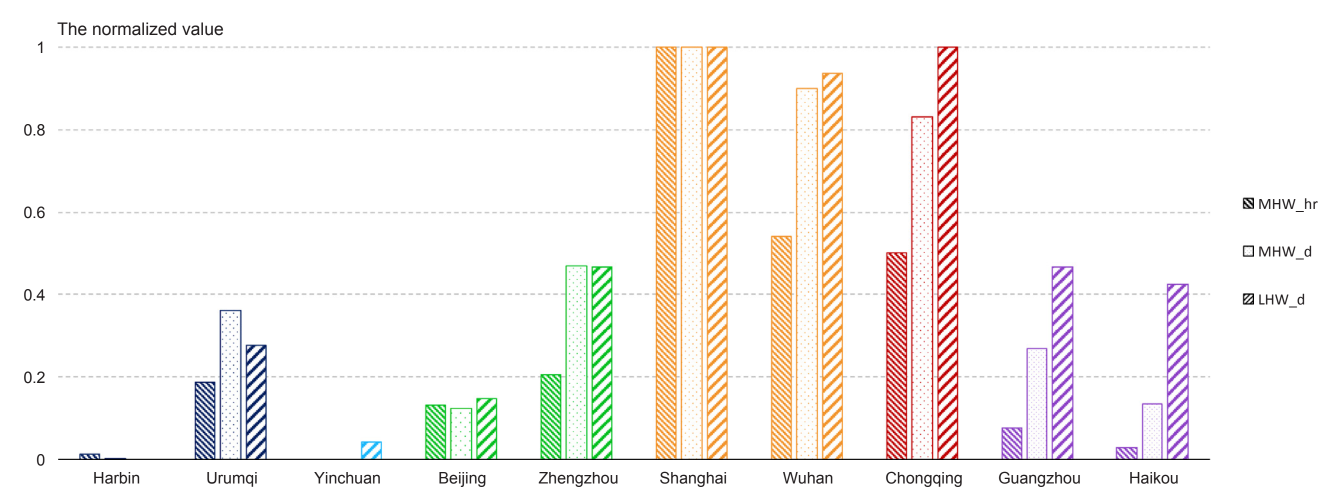


Fig. 14. The most severe extreme event in each city (the indices are normalized for comparison).

engineers to check working condition during heat wave events. For example, the PV heat pump system is a new kind of cooling appliance and can be promoted in solar-rich zones in future. However, the efficiency of both the PV system and the air-source heat pump will decrease when the outdoor temperature is above 30 or 35 °C [74]. Thus, it is needed to simulate the real efficiency of the equipment during extreme heat to have a better understanding of the indoor environment and cooling load.

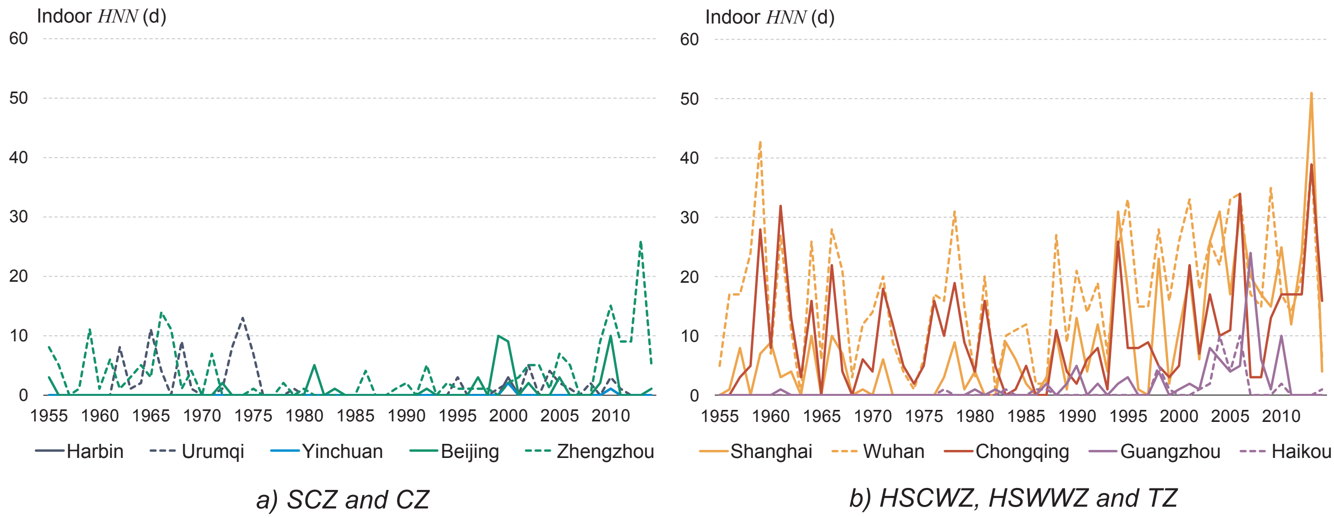


Fig. 15. The number of hot nights (HNN) over 60 years.

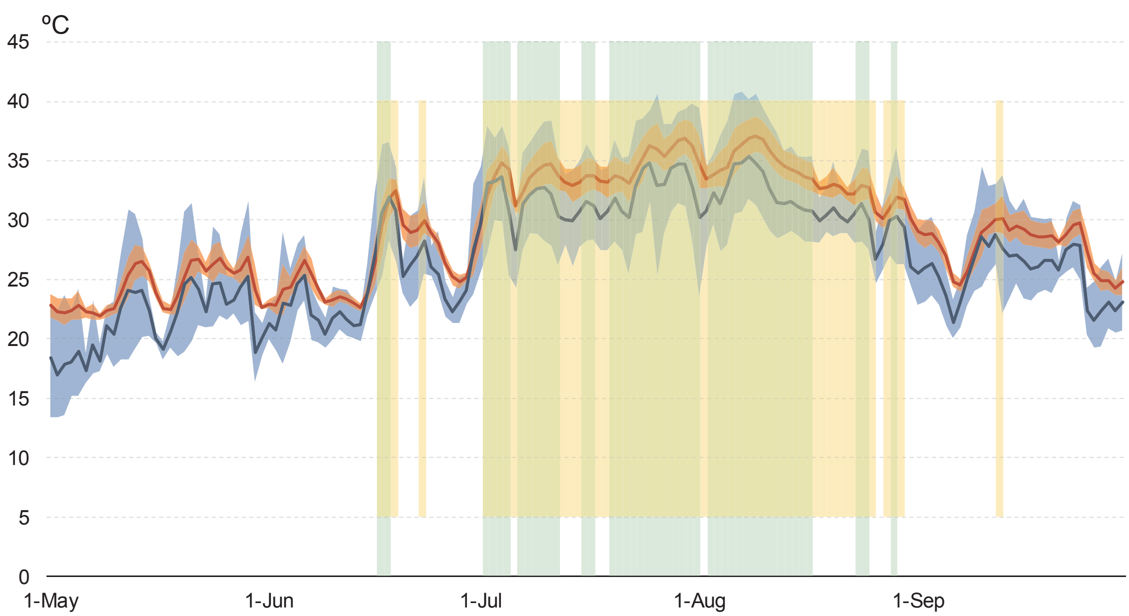


Fig. 16. Indoor and outdoor temperatures in Shanghai in 2013. Notes: the blue shadow represents the outdoor temperature range each day and the blue line represents the average outdoor daily temperature, the orange shadow and line represent the indoor situation, the green shadow represents the outdoor heat wave and the yellow shadow represent the indoor heat wave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Different building envelopes in the selected cities.

City	Building performance	U-value (W/m^2 K)			Window SHGC	Ventilation rate closing the window (ACH)
		Roof	Wall	Window		
Harbin	Former standard	0.50	0.52	2.5	0.59	0.5
	Current standard	0.30	0.45	1.9	0.59	0.5
	Future standard	0.25	0.30	1.5	0.45	0.3
Beijing	Former standard	0.60	0.90	3.2	0.59	0.5
	Current standard	0.45	0.60	2.5	0.45	0.5
	Future standard	0.30	0.45	1.9	0.40	0.3
Shanghai	Former standard	1.0	1.5	3.5	0.45	1.0
	Current standard	0.8	1.0	3.2	0.40	1.0
	Future standard	0.6	0.7	2.8	0.35	0.5
Guangzhou	Former standard	1.2	2.0	4.0	0.35	1.0
	Current standard	0.9	1.5	3.5	0.20	1.0
	Future standard	0.7	1.0	3.2	0.18	0.5

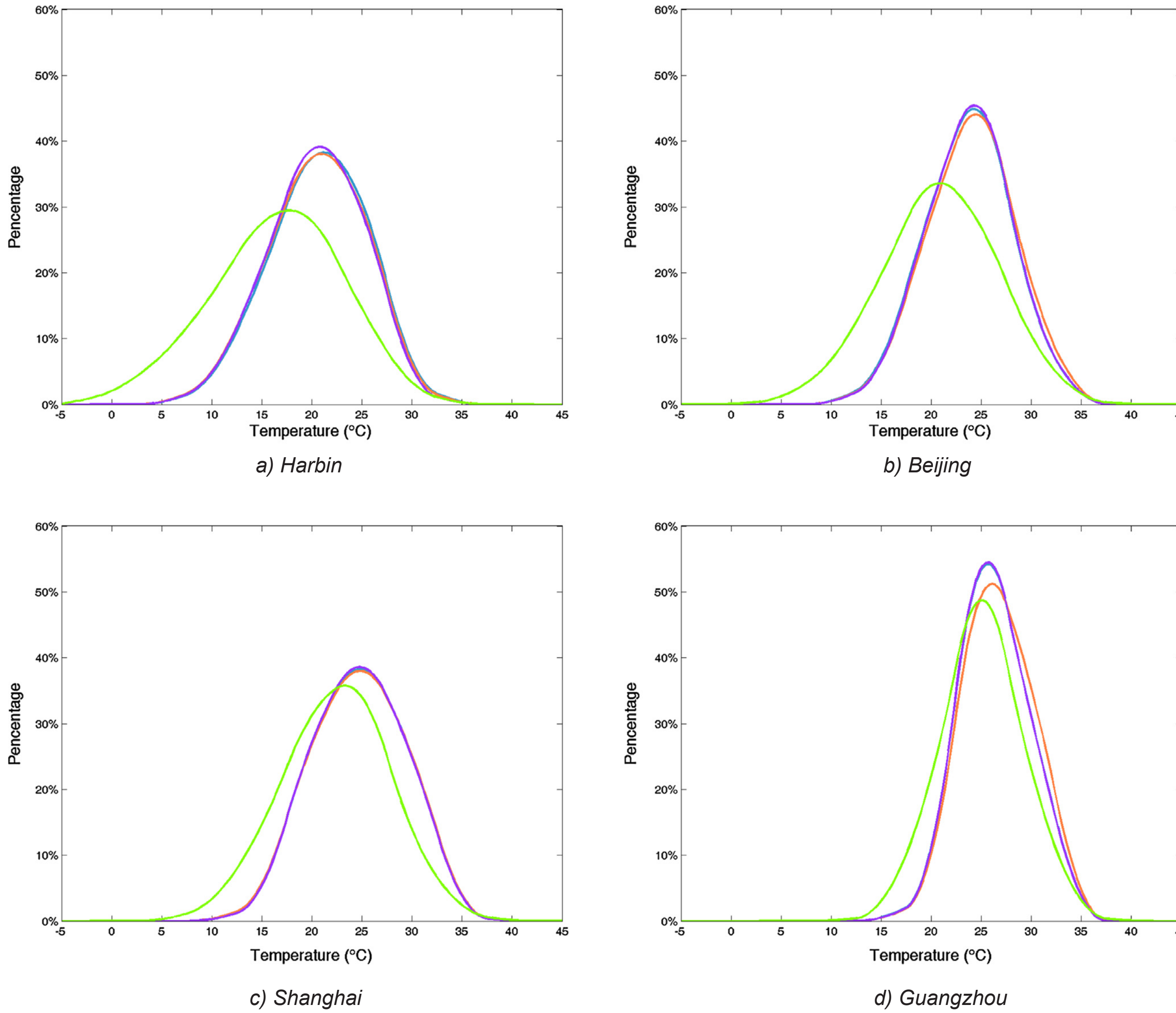


Fig. 17. The distribution of indoor temperature in cities in different building envelopes. Notes: Green lines are for outdoor, blue lines for current standards, orange lines for former standards and purple lines for advanced standards. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This study has several limitations. Firstly, the method used is based on multi-decade historical weather data, which may not accurately reflect future heat wave events considering global and local climate changes. Thus, predictive multiple year weather data may be needed for further research. Secondly, in this study, several indices are defined to evaluate the heat wave situation. The parameter and the upper line of the indoor environment used in the indices are also worthy of further discussion. With different parameters and lines, the results may be different, reflecting the results of evaluating the indoor environment and comparing the indoor and outdoor situation. The results of thermal comfort theory can be used to improve the science and rationality of the indices. A more in-depth explanation of the changes in the heat waves for the indoor environment in different locations with different building envelope performance and occupancy patterns is needed. The building envelope performance studies include but not limited to the building shape and the exterior shading. Occupant behavior patterns (e.g., open window and use shading) may change during the extreme heat events which further influence the indoor environment. In addition, the existing research has shown that heat waves can be affected by urbanization, economic development, population growth, etc. The manner in which these parameters affect the indoor thermal environment is another open and important problem which should be investigated.

5. Conclusions

In this study, a novel approach was developed to determine typical hot year weather data for use in evaluating heat wave impact on the indoor thermal environment in China's residential buildings. The approach is different from traditional approaches that focus on outdoor weather data. The free-floating (no cooling) indoor thermal environment in a typical residential building was simulated using 60 years of actual weather data from 12 cities in China. Seven indices from different aspects of the heat wave situation were defined and calculated using the simulation results. In addition, three kinds of typical hot years were selected with different focuses.

The simulation results show that the derived heat waves data are different from the outdoor-based results. Both outdoor temperature and solar radiance affect the indoor situation. In this study, the heat wave situation is not sensitive to the building envelope performance (insulation and ventilation rate), which may be related to the occupant's

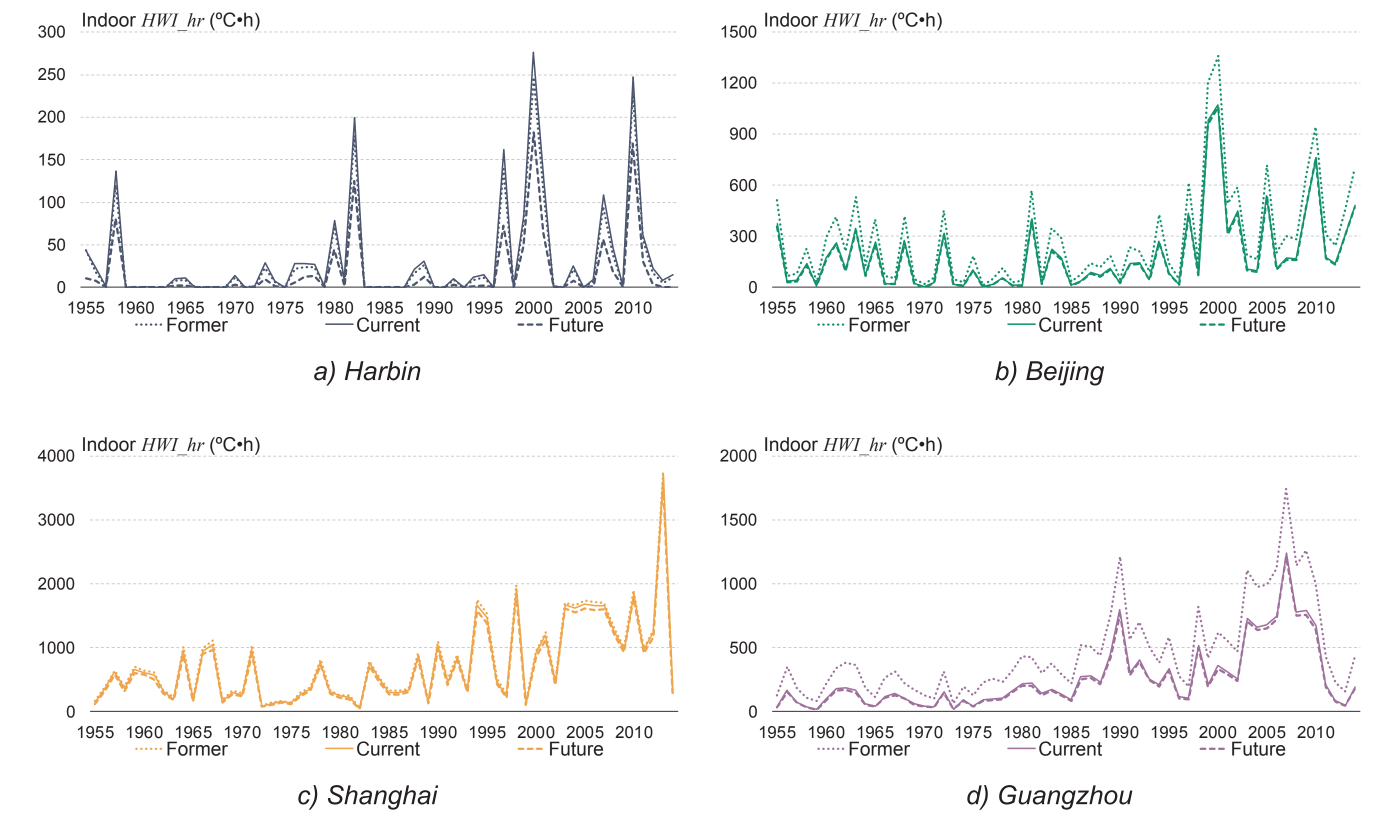


Fig. 18. The heat wave indices of four cities with different building envelopes.

Table 4
THYs in different cities based on the indoor and outdoor air temperatures.

City	THY-I		THY-E		THY-N	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Harbin	2000	2010	2000	2010	2000	/
Urumqi	1974	1974	1974	1968	1974	1974
Yinchuan	2005	2014	2000	2000	2000	/
Beijing	2000	2000	1999	1999	1999	2010
Zhengzhou	2013	1966	2013	1966	2013	2013
Chongqing	2006	2006	1994	1994	2013	2006
Wuhan	1959	1959	2013	2013	1959	2005
Shanghai	2013	2013	2013	2013	2013	2006
Guangzhou	2007	2004	2007	2005	2007	2007
Haikou	2005	2005	2006	2005	2006	1998

Notes: For Harbin and Yinchuan, when using outdoor weather data, there is no hot night according to the definition in this study.

behavior (in China, occupants typically open windows when temperatures are elevated and the outdoor is cooler) assumed in this study. Further, the determined annual weather data representing the impact of heat waves can be used to evaluate the indoor thermal environment and cooling demand during the extreme heat events.

To the best of the authors' knowledge, this is the first paper to focus on the impact of heat waves on the indoor thermal environment using long-term historical weather data, which shows the difference between the outdoor and indoor during extreme heat with quantitative description. The results show that the differences do exist and the indoor environment should be paid more attention. Meanwhile, there hasn't been studies to analyze the indoor situation in China, as China's building performance and occupant behavior are different from other countries, and both influence the indoor environment. In addition, this study emphasizes the importance of indoor environment during night, which is the main difference between the outdoor and indoor and has a great influence on people's health at home.

For future studies, the simulated future weather data could be used to reflect the impact of climate change and the indices used in this study could be modified. The efforts of building performance and occupant behavior, as well as other related parameters are also worthy for further studies.

Acknowledgments

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